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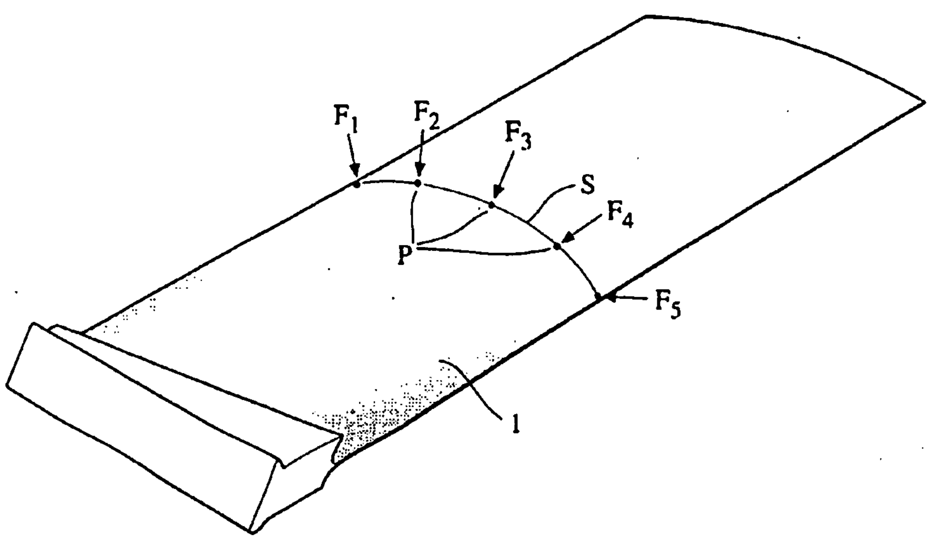

(57) Abstract

In workshop engineering production of a part (1), a robot is instructed to carry out subsequent machining (grinding, deburring) of the part by handling the part via an arm provided with a force sensor and, according to a program stored into the robot, operating the part to adopt a definite position in space in a converting machine in such a way that the machine within given tolerances machines the surface of the part. The outer contour (S) of the part, in sweeps across the surface of the part selected by the operator, is read and stored into the program of the robot at few points (P) per sweep. A given contact force (F_a), the magnitude and direction in space of which are determined, between the part handled by the robot and the tool of the converting machine is programmed for each point (P), whereby the programmed contact force, the force and direction of which are determined, forces the robot, instead of compensating for the deviation of the contact point from the outer contour of the part, to uninterruptedly carry out the machining along the actual contour (S) of the part with the programmed contact force.

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Automatic subsequent machining of blades for rotating machines

TECHNICAL FIELD

The present invention relates to the operation subsequent machining, such as grinding and deburring, of finally shaped parts, preferably blades in rotating machines, in workshop engineering production.

BACKGROUND ART

In workshop engineering production of parts, after the part has received its final shape by, for example, milling, turning or some other type of material removal, there is usually required a subsequent machining in the form of any of the operations deburring, grinding and polishing. The parts referred to in this description preferably consist of machine elements in the form of blades, which control flows of media. The concept blades then also comprises both blades and guide vanes for steam and gas turbines, as well as other types of blades, vanes and propellers for pumps and other variants of rotating machines. Characteristic of these blades is that they often exhibit double-curved surfaces.

Currently, subsequent machining of the above-mentioned parts is for the most part performed manually in operations in which, for example, staff grind finally shaped blades, one at a time, by moving the surfaces of the blade against grinding tools attached to converting machines. These converting machines consist of abrasive belt grinders or machines which support grinding tools in the form of grinding wheels. In a production unit for, for example, turbine blades, as large a part as one-fourth of the labour force may be engaged in the operations deburring and grinding. Since the blades which are to be machined may be heavy, this may result in strain

injuries, which makes it desirable to bring about a change of the working environment.

To address the problems of the working environment, to obtain a more uniform quality and to achieve a more rational manufacture with increased competitiveness, it is desirable to automate the subsequent machining operations.

One of the problems of automating the subsequent machining of blades is that the number of uniformly shaped blades in a production batch is small and that the richness of variations of blades of different models is very great (> 5000). In order for an automated subsequent machining to constitute an alternative, however, the costs of programming of the equipment, gripping devices and ancillary units must be kept low. Other problems are, as mentioned, model variations as well as the variations with respect to the physical size of the parts and the variations in machining technique.

Non-manual methods for subsequent machining are already available. As an example may be mentioned electrolytic surface deburring. However, this methods entails the use of chemicals which are dangerous to health and therefore does not constitute an attractive alternative to a solution of the problem of subsequent machining.

A further method for dealing with non-manual subsequent machining of blade parts consists of the tumbling technique. However, this method can only manage subsequent machining of the foot and roof of, for example, turbine blades. Also with this method a liquid is usually used, in this case with the function of binding dust. The discharge of such liquids requires permission. For that reason, tumbling is not a suitable technique for automation either.

Automatic grinding machines for subsequent machining of blades of the types mentioned above are available on the market. A special machine of this kind is marketed by the Swiss company Liechti and is described in the European patent with publication number EP 483064. However, this machine can only handle blades longer than 150 mm and, further, can only grind the blade itself and the blade walls on a blade, not the roof or the foot when these occur on the blades. In addition, the machine is expensive and requires special equipment.

Previously, deburring and grinding, where industrial robots have been utilized, has been carried out either with stiff tools in resilient tool attachments or with soft tools of the type fibreboard and the like. The resilience aimed at is required in order for small mutual variations in the geometry of the machined parts to be tolerated, and to compensate for inaccuracies in fixtures, gripping devices and robot movements. The heavy requirement for precision has brought about an accurate, extensive and time-consuming programming of the robots which have been utilized in these operations. However, it has proved that problems still arise when using hard tools, since difficulties in achieving uniform and repeatable results have revealed themselves. Also when utilizing soft tools, problems have arisen. In this case, the tool wear has constituted the major stumbling-block. Recently, however, new facilities have appeared on the market, which have created new conditions for automation of deburring and grinding operations with the aid of industrial robots. The methods in question are all referred to as "constant-force methods". The facilities developed can be used together with practically all of the robots existing at present. However, this is not true of the most complex facilities, the so-called force sensors, which are greatly dependent on the control system of the robot to function satisfactorily. Among the principal

advantages of these "constant-force methods" and the facilities mentioned here may be mentioned:

- automated compensation for tool wear
- automated compensation/inherent tolerance towards inaccuracies
- simplified programming and erection.

The force-sensing equipment which is utilized in connection with the above-mentioned "constant force methods" may be divided into two main groups, namely, constant force units, also called micromanipulators or CFDs (Constant Force Device), and real-time working sensors, which are also called force sensors.

If constant force devices (CFDs) are used in converting machines together with a standard robot, such CFDs must be installed at each converting machine, for example, at each grinding point. If, on the other hand, a CFD is installed in a tool-carrying robot between the robot arm and the tool, no sufficient control is obtained of the machining, since a CFD can only correct the force in one direction in relation to the tool, not in a constant direction in space (i.e. not in a constant vector in space). As examples of prior art in which mechanical machining is carried out with the aid of industrial robots which are equipped with constant-force sensing members may be mentioned Richard C. Dorf, International Encyclopedia of Robotics: Applications and Automation, Vol. 1, 1988, John Wiley & Sons, page 527, and US 4,967,127. The former publication also discusses the problems which occur within the force sensing technology.

To remedy the problems mentioned above, the method according to the invention has been based on the use of a force sensor because, at a reasonable cost, the following advantages are obtained with the method:

- reduced number of points on the contour of a part which need to be read into the memory of the robot
- reduced requirement for accuracy in teaching the points
- less expensive gripping devices and fixtures, and
- inherent tolerance towards small variations in the geometry of the machined parts.

Force sensors as force-sensing equipment make use of the robot arm, on which the force sensor is mounted, as adjusting object. The robot must then in some way receive indications as to (sense) how the force between the tool and the part in the machining operation varies in order to be able to adjust the force in question, that is, the actual value, to the desired force, the desired value. Contrary to the previously described group of force-sensing equipment, CFDs, the system with force sensors does not work on all robots. The control system of the robot must be adapted to work integrated with a force sensor.

A force sensor is always attached to the robot arm between the tool/gripping device and the tool plate of the robot. The sensor senses forces in three directions in space and torques around three axes in space.

SUMMARY OF THE INVENTION

The method according to the invention comprises an automated subsequent machining, for example grinding, deburring and polishing, of a finally-shaped part in workshop engineering production of the part, wherein a robot is instructed to carry out subsequent machining of the part by handling the part via an arm provided with a force sensor and operating the part, according to a program stored in the robot, to adopt a definite position in space at a converting machine in such a way that the machine within given tolerances machines the surface of the part. The method is characterized in that

the outer contour of the part, in sweeps selected by the operator across the surface of the part, is read and stored into the program of the robot at a small number of points per sweep, which points together form a polygon curve, and in that a given contact force, the magnitude and direction in space of which are determined, between the part handled by the robot and the tool of the converting machine is programmed for each point, whereupon, during the machining, the robot strives to move the part towards the converting machine such that the contact point between the part and the tool of the machine in each machining sweep lands on the polygon curve, whereas the programmed contact force, the force and direction of which are determined, forces the robot, instead of compensating for the deviation of the contact point from the polygon curve, to uninterruptedly carry out the machining along the actual contour of the part with the intended machining force in the intended direction towards the tool.

The object of the method is to address the programming problem, by reducing the necessary number of taught points and reducing the need of positional accuracy radially to the tool when teaching the points, and to allow force-sensing equipment to attend to the compensations which are required to keep the force between the tool and the machined part constant in a certain direction in space (towards the tool).

The method with subsequent machining according to the invention is most advantageous when the robot which handles a part has access to the reference surfaces and reference lines with which the part can be provided according to Swedish patent application 9300356-4, which describes in detail that during the machining operation a fixture and reference extension is applied to the part, through which the handling machine at all times has information about the position of the part in space.

The compensations involved may comprise correction of the position of the robot arm with the associated part fixed to the arm during the operation on the basis of the feedback obtained from the force sensor, such that the contact force (as vector) between the part and the tool is kept constant.

Subsequent machining according to the invention is possible

- if the parts are machined into accuracy of shape and dimensions prior to the subsequent machining
- if the subsequent machining is of a surface-improving nature only
- if the subsequent machining of such components as, for example, the foot and/or roof of a blade is to comprise deburring/edge breaking and the creation of edge radii only.

If, for example, the blade profile of a turbine blade is to be ground, this usually means that the robot is to grind the blade profile along curved surfaces. The robot must be able to follow the curvature of the profile as accurately as possible to prevent any uncontrolled additional cutting of blade material, or to prevent the load from becoming so great that the tool is worn down too rapidly because of too heavy contact forces, or to prevent the contact force from becoming too small. To manage this, the robot must be taught to find a number of points on the periphery of the blade profile. In conventional robot programming, the taught points, which of necessity are limited in number, are interconnected by straight lines and/or circular arcs to describe the path that the robot is to follow. The more curved a contour is, the more closely together the taught points have to be placed in order for the movements of the robot during the operation to be sufficiently accurate. In addition, it is important that the positions of the points in space are read very carefully; otherwise, a quality deficiency will be built into the robot

even during the programming of the robot. If, on the other hand, some type of force sensing is used together with the robot, it is sufficient to read in only few points on the periphery of the profile (see the description of the figures below).

The method according to the invention, in which the robot holds the workpiece, also means that it will be necessary to employ a skilled operator during the subsequent machining operation, who, during the programming, can move the robot arm with the workpiece towards the machining tool and thereby adjust the workpiece at each selected programming point in such a direction and adjust the machining force with such a magnitude as the operator would have used himself during a corresponding manual operation.

If a robot with force sensing facilities, used according to the invention, is combined with tools adapted to the method, it turns out that subsequent machining with a robot is possible. A robot with a force sensor normally operates with forces down to 10 N. Since a high accuracy is required, this means that a combination, for example with rotating files and similar tools operating with small contact forces, is not suitable. To optimize the subsequent machining according to the method, wide tools, such as abrasive belts, wide grinding wheels, circular hubs and the like should be used. When such wide tools are utilized, the machining forces (the surface pressure) can be kept at a level which is favourable for the force-sensing equipment.

Tools with favourable properties are tools which

- are non-deforming
- have the ability to create radii instead of facets
- have the ability to break edges without having the follow a complicated contour accurately

- have tolerance towards different forms of inaccuracies.

By non-deforming tools are meant tools which, during a subsequent machining, may not change the shape or dimensions of the part in any proper sense. Of course, these tools also cut material, but to a very small extent. As an example, during grinding operation, may be mentioned that a fibre-based grinding wheel may achieve a cutting depth on the surface of the part of the order of magnitude of 0.01 mm, which is quite acceptable. For grinding and deburring applications, a number of suitable tool alternatives are available. These consist of abrasive belts and grinding wheels, which are built up of fibres with abrasive bound to the fibres and abrasives built up of polymeric grinding materials. Ceramic grinding wheels and more aggressive conventional abrasive belts are less suitable for use during subsequent machining with a robot.

During manual deburring and grinding of radii on edges, rotating or oscillating files are often used. This functions well when it comes to breaking an edge, but not when it comes to creating a true radius. If the work takes place manually, the operator may "build up" a radius with a file by faceting the surface. If the work is to be automated with the aid of a robot, the problem becomes considerably more difficult. The robot lacks the "finger-tip feel" that the operator possesses, although resilient tool attachments are used. This necessitates a moderate velocity of movement of the robot, if the edge to be deburred is curved. In addition, the programming work becomes more extensive and more difficult. During this type of operations, it is desirable to use a tool with the ability to create a radius, without the robot having to pass along the edge several times at different contact angles. Also for this type of operation, fibre- or polymer-based grinding wheels are suitable alternatives.

One advantage with the method according to the invention, in which the workpiece is carried by the robot arm, is that many of the disadvantages which known methods with tool-carrying robots are characterized by are avoided. A tool-carrying robot has difficulty in managing the same degree of unmanned production as a part-carrying robot since the tools (abrasive belts, grinding wheels etc.) which a tool-carrying robot can use may be of the same dimensions, the same life, etc., as the tools which are used in a specially equipped machine tool. A machining tool for grinding may, for example, be equipped with over 5 m long abrasive belts. If a tool-carrying robot were to be equipped with tools with a service life comparable to the service life of the tools which a fixed, specially equipped machining tool may use, these tools would be large and clumsy. This, in turn, would entail deteriorated accessibility around the fixture in which the workpiece is mounted during machining.

To sum up, it can be mentioned that some type of resilient tools are suited for subsequent machining according to the invention.

Among the advantages achieved by means of the method may be mentioned the possibility afforded by the concept of imitating man´s ability to maintain an almost constant machining pressure against a tool, while at the same time largely eliminating work which is dangerous from an ergonomic point of view.

BRIEF DESCRIPTION OF THE DRAWING

Figure 1 illustrates the programming requirement, that is, the requirement for taught points on a profile of a part which is to be subjected to subsequent machining according to the prior art.

Figure 2 shows an example of the considerably reduced requirement for taught points on a profile surface during subsequent machining according to the invention.

Figure 3 schematically illustrates a turbine blade over which a sweep along a contour curve (S) is programmed, wherein at a small number of points (P) along the sweep the machining forces F_1 to F_5 have been inserted. The forces F_1 to F_5 are programmed into a robot for subsequent machining.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

According to one embodiment, there is described how a subsequent machining operation can be arranged according to the method, in which the profile of a turbine blade (1) with a cross section according to Figure 2 is to be ground after the blade (1) has been machined into accuracy of shape and dimension.

A robot with at least five axes grips the blade with its gripping device. The methods to be used during the grinding are decided, whether the blade is to be ground in transversal or longitudinal sweeps when moving the blade against the grinding tool. The grinding tool then preferably consists of an abrasive belt with a width which is adapted to the type of the blade. If the blade is not twisted, a wide abrasive belt can be used, in certain cases with such a width that only one sweep is necessary. If, on the other hand, the blade is twisted, the width of the abrasive belt is adapted thereto, taking into consideration that multi-point contact with the grinding tool is to be avoided.

The programming of the robot movements is made by an operator skilled in manual grinding technique. This operator now controls the robot such that the blade is brought towards the abrasive belt until contact is achieved with the abrasive

belt at a contact roller. This contact is then selected at a point (P) in a first sweep, in which a sweep may consist of a curve across the back of the blade profile or the inside of the blade profile across the blade, or of a longitudinal sweep from the foot of the blade to the roof thereof. The skilled operator is then knowledgable about the direction in which the tool is to engage the surface of the blade profile and, at the selected point, turns the position of the blade in space (with the aid of the robot control member). Then, the operator stores into the robot memory the position of the blade (1) in space. The next point (P) in the sweep and the contact force F_1 - F_5, at which the robot between the selected points (P) is to act, are stored. The storage of additional points (P) in the sweep proceeds in the same way, with transmission of information to the robot about the position of the blade and the desired contact force F_1 - F_5. Figure 2 shows that according to the invention it is sufficient to store only few points (P) per sweep. As is clear from Figure 2, with the profile shown in the example, a guiding value for the need for stored points (P) may be given as 3-5 points (P) on the back of the blade and three points (P) on the underside thereof. If the blade profile is greatly curved, the need of points increases and vice versa. If the blade is not twisted, it is, in addition, possible to program only movements in the lateral direction where additional sweeps with the same machining information are stored. There is also fed into the robot information about the velocity of movement of the robot between stored points (P), how it is to move from point (P) to point (P), in which order, whether the robot is to move the part against the tool rectilinearly or along some other known path from point to point, and how values of forces are to be selected in the sweep between two points P. The number of revolutions of the converting machine, in this case the speed of the abrasive belt, can also be controlled from the robot, after such information has been stored into the robot program. It may be desirable to vary the speed of

the grinding tool over different portions of the profile. Furthermore, adjustment of the belt speed can be programmed for adaptation to the wear of the grinding tools over time or over the number of ground parts.

The value of the contact force, that is, its magnitude and direction, between the programmed points P in a sweep over the blade 1 may, for example, be selected such that both magnitude and direction linearly change from the values thereof at a preceding point to the values which apply to the succeeding point. Another way of using force information between two points P is that the last force set is valid until new and deviating force information is received upon passage of a new point P in the machining sweep.

As illustrated in Figure 2, relatively great deviations from the true periphery can be tolerated during programming and teaching of points (P). This also means that a certain inaccuracy can be tolerated when determining the position of the programmed contact point (P) between the blade and the tool. This saves much time when teaching points.

The procedure described may constitute a rough grinding operation. When changing to fine grinding of the same rough-ground part, the already stored program can be used. The only difference is that during this operation, a movement towards another grinding machine with finer grinding tools is stored into the robot memory. In this fine grinding machine, a machining operation with movement and information patterns corresponding to those during the rough grinding operation is repeated.

The back and the inside of the blade are machined in two different steps. During start-up and termination of a sweep across the blade, the blade is moved at right angles to and out from the tool, respectively, at such a distance from the

inlet edge and the outlet edge that these edges are not machined. The inlet and outlet edges are machined in grinding steps separated from the machining of the surfaces of the back and the inside.

For subsequent machining of such portions as the foot and the roof of, for example, turbine blades in the form of deburring and/or edge breaking, the procedure during programming and subsequent machining operations is, in principle, the same as during the above-mentioned rough grinding. In these cases, however, other types of grinding tools are used, such as polymer-based abrasives. Suitable such abrasives have proved to be of a type which is marketed under the name Scotch-Brite wheels for machining edges where the angle is > 90° and polymer fibre brushes for edges with an angle of < 90°.

According to the embodiment, the equipment utilized for the process possesses certain properties in order for a good result to be obtained. The robot in the system should have at least five axes. When testing the method according to the invention, a six-axis, anthropomorphic robot with a handling capacity of at lest 60-70 kg has been used. The control system of the robot must be adapted for communication with a force sensor. Grippers which are designed according to the description of the above-mentioned Swedish patent application 9300356-4 are recommended.

The ancillary equipment of the robot consists in the example of an abrasive belt grinder for grinding blade profiles, a two-spindle grinding machine for deburring/edge breaking and radius grinding of the foot and roof (on one spindle of the grinding machine a grinding wheel being mounted and on the other spindle a polishing brush being mounted), and finally a two-spindle grinding machine with a grinding wheel for grin-

ding transitions towards blade walls. Otherwise, magazines are used which accommodate all blades in an entire production batch. The magazine is designed to suit as large a number of variants of blades as possible.

CLAIMS

1. A method for automated subsequent machining, for example grinding, deburring, polishing, of a finally-shaped part (1) in workshop engineering production of the part (1), wherein a robot is instructed to carry out subsequent machining on the part by handling the part via an arm provided with a force sensor and, according to a program stored in the robot, operating the part to adopt a definite position in space at a converting machine in such a way that the machine within given tolerances machines the surface of the part, **characterized** in that the outer contour of the part, in at least one machining sweep (S), is read and stored into the program of the robot at a small number of points (P) per sweep (S), wherein the points (P) in each sweep form a polygon curve (C), and that a given contact force, the magnitude and direction in space of which are determined, between the part handled by the robot and the tool of the converting machine is programmed for each point (P), whereupon during machining the robot strives to move the part towards the converting machine such that the contact point between the part and the tool of the machine lands on the polygon curve (C), whereas the programmed contact force, the force and direction of which are determined, forces the robot, instead of compensating for the deviation of the contact point from the polygon curve, to uninterruptedly perform the machining along the actual contour (S) of the part with a contact force (F_1 - F_5), the magnitude and direction of which are set.

2. A method according to claim 1, **characterized** in that the contact force which is programmed into the robot is the same during a machining sweep or that the contact force is determined for each individual distance between programmed points (P).

3. A method according to claim 1 or 2, **charact rized** in that this comprises subsequent machining of blades (1), which preferably consist of blades and guide vanes for steam and gas turbines.

4. A method according to claim 3, **characterized** in that the subsequent machining comprises any of the machining operations grinding, deburring, edge breaking and the creation of edge radii.

5. A method according to claim 1, **characterized** in that the robot when handling a part grips said part at a fixture extension which is provided with references containing information about the position of the part in space.

6. A method according to claim 1, **characterized** in that the tools of the converting machine are of a non-deforming nature, for example fibre or polymer-based grinding tools.

7. A method according to any of the preceding claims, **characterized** in that the converting machine in the method consists of an abrasive belt grinder and/or a two-spindle grinding machine for grinding wheels.

Fig. 1

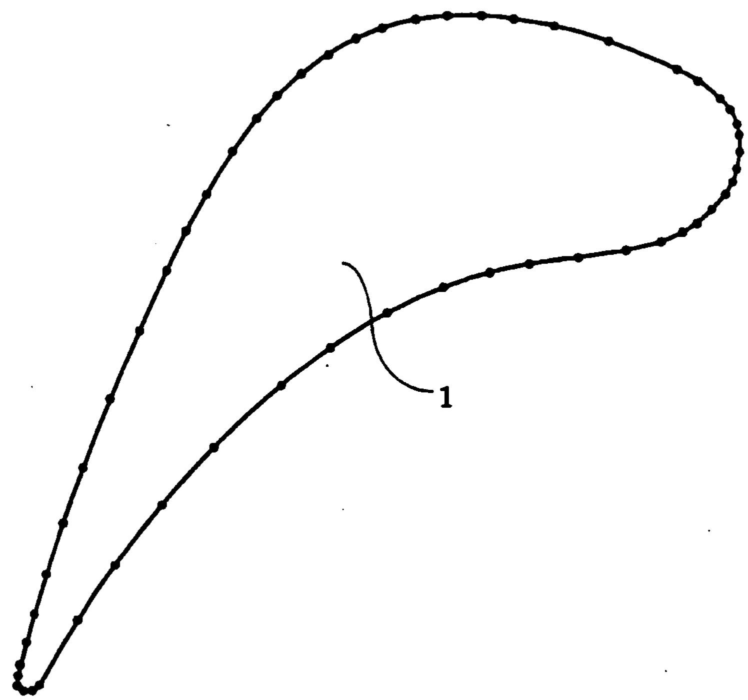


Fig. 2

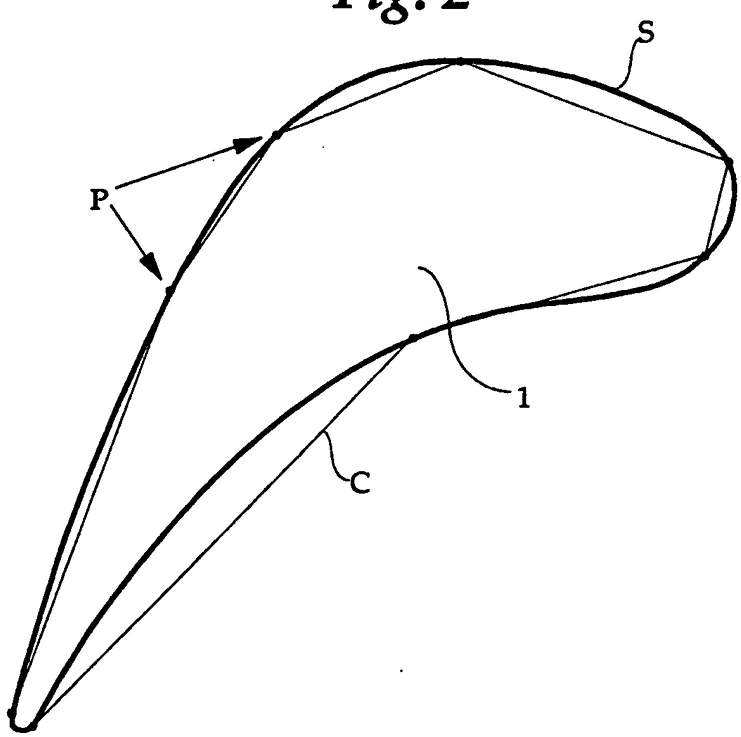
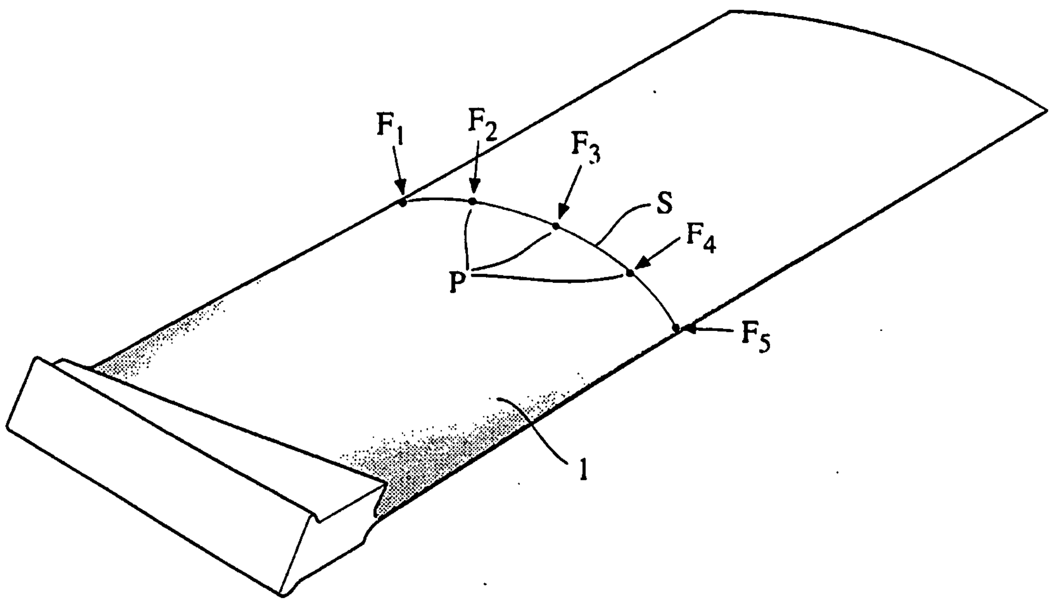


Fig. 3



INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER

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B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC : B24B, B25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

DIALOG

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	INTERNATIONAL ENCYCLOPEDIA OF ROBOTICS Richard C. Dorf, New York 1988 See page 525-530 (especially 527) and 1544-1563 (especially 1545, 1561) --	1-7
A	US, A, 4897586 (SHUICHI NAKATA ET AL), 30 January 1990 (30.01.90), abstract --	1-7
X	DD, A1, 273224 (KOMBINAT FORTSCHRITT LANDMASCHINEN), 8 November 1989 (08.11.89), abstract --	1-7

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
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INTERNATIONAL SEARCH REPORT

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE, A1, 3906438 (DAIMLER-BENZ AKTIENGESELLSCHAFT), 13 Sept 1990 (13.09.90), abstract --	1-7
X	US, A, 4967127 (YASUO ISHIGURO), 30 October 1990 (30.10.90), claim 1 -- --------	1-7

INTERNATIONAL SEARCH REPORT

Information on patent family members

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